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Linking an Economic and a Life-cycle Analysis Biophysical Model to Support Agricultural Greenhouse Gas Mitigation Policy

Kombination eines ökonomischen Modells mit einem bio-physikalischen Lebenszyklus-Modell zur Unterstützung von Politikmaßnahmen zur Verringerung von Treibhausgasen

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Abstract

Greenhouse gas (GHG) mitigation is one of the main challenges facing agriculture, exacerbated by the increasing demand for food, in particular for livestock products. Production expansion needs to be accompanied by reductions in the GHG emission intensity of agricultural products, if significant increases in emissions are to be avoided. Suggested farm management changes often have systemic effects on farm, therefore their investigation requires a whole farm approach. At the same time, changes in GHG emissions arising off-farm in food supply chains (pre- or post-farm) can also occur as a consequence of these management changes. A modelling framework that quantifies the whole-farm, life-cycle effects of GHG mitigation measures on emissions and farm finances has been developed. It is demonstrated via a case study of sexed semen on Scottish dairy farms. The results show that using sexed semen on dairy farms might be a cost-effective way to reduce emissions from cattle production by increasing the amount of lower emission intensity 'dairy beef' produced. It is concluded that a modelling framework combining a GHG life cycle analysis model and an economic model is a useful tool to help designing targeted agri-environmental policies at regional and national levels. It has the flexibility to model a wide variety of farm types, locations and management changes, and the LCA-approach adopted helps to ensure that GHG emission leakage does not occur in the supply chain.

Key words

greenhouse gas mitigation; dairy farms; marginal abatement cost curves; life cycle analysis; whole farm modelling

Zusammenfassung

Die Verringerung der Emissionen von Treibhausgasen (THG) ist eine der wichtigsten Herausforderungen für die Landwirtschaft, vor allem wegen der steigenden Nachfrage nach Lebensmitteln, insbesondere für tierische Erzeugnisse. Eine Ausweitung der Produktion muss von einer Verringerung der THG- Emissionsintensität landwirtschaftlicher Erzeugnisse begleitet werden, um die Zunahme von Emissionen zu vermeiden. Änderungen im Management wirken oft auf den ganzen landwirtschaftlichen Betrieb. Die Untersuchung hat diesem Umstand Rechnung zu tragen. Änderungen der THG-Emissionen in vor- und nachgelagerten Bereichen können auf Veränderungen im Management landwirtschaftlicher Betriebe zurückzuführen sein. Im Beitrag wird ein Modellierungszugang vorgestellt, der den gesamten Betrieb, den Lebenszyklus der Produkte und Auswirkungen der THG-Minderungsmaßnahmen auf Emissionen und wirtschaftliche Erfolgsgrößen quantifiziert. In der Fallstudie werden Auswirkungen des Einsatzes von gesextem Sperma in schottischen Milchviehbetrieben untersucht. Die Analyse zeigt, dass gesextes Sperma ein kostengünstiger Weg ist, um die Emissionen in der Rinderproduktion zu senken, und zwar durch geringere Emissionsintensität der Kuppelprodukte Milch - Rindfleisch. Die Ergebnisse zeigen den Vorzug eines Modellierungsansatzes in dem eine THG-Lebenszyklus-Analyse und ein Betriebsmodell kombiniert werden. Dies kann dazu dienen, Maßnahmen der Agrarumweltpolitik auf regionaler und nationaler Ebene gezielt einzusetzen. Der Zugang verfügt über die Flexibilität, eine Vielzahl von Betriebstypen, Standorte und Management-Veränderungen zu modellieren. Die Lebenszyklus-Analyse hilft, allfällige THG-Leckage-Effekte in der Versorgungskette aufzudecken.

Schlüsselwörter

Treibhausgasemission; Milchviehhaltung; Grenzvermeidungskosten; Lebenszyklus-Analyse; landwirtschaftliche Betriebsmodellierung

List of Abbreviations

CH_4	*methane*
CO_2	*carbon dioxide*
EI	*emission intensity*
FAO	*UN Food and Agriculture Organisation*
FAS	*Farm Account Survey of Scotland*
GHG	*greenhouse gases*
GLEAM	*Global Livestock Environmental Assessment Model*
IPCC	*Intergovernmental Panel on Climate Change*
LCA	*life cycle analysis*
LP	*linear programming*
N	*nitrogen*
N_2O	*nitrous oxide*

1 Introduction

Reducing greenhouse gas emissions arising from agricultural activities remains a challenge as the world is starting to experience the consequences of a changing climate (IPCC, 2013) and at the same time food production is facing major challenges both in demand for land-based products and also in terms of production constraints (FORESIGHT, 2011). Satisfying growing demand for livestock products will lead to significant increases in the greenhouse gas emissions from the sector unless the emission intensity (i.e. the GHG emissions arising from the production of a unit of output, e.g. kg CO_2e (litres of milk)$^{-1}$) can be reduced.

Globally, cattle milk is the largest source of livestock protein and global milk demand is forecast to increase by 80% by 2050, relative to 2005/7 demand (ALEXANDRATOS and BRUINSMA, 2012). The greenhouse gas emissions arising from global milk production were quantified by GERBER et al. (2010) and increasing attention is being paid to finding ways of reducing the emission intensity of milk production.

Numerous management changes and technologies have been proposed to reduce on-farm emissions from livestock (see for example BELLARBY et al., 2013; COTTLE et al., 2011; HRISTOV et al., 2013). A few measures only affect one emission source on the farm; for example reducing excess nitrogen fertiliser decreases nitrous oxide emission without any further implications on the other activities on farm. However, many measures can have system-wide effects, e.g. changing the ration can lead to changes in enteric methane emissions, changes in volatile solid and N excretion rates (with consequent impacts on manure CH_4 and N_2O emissions), and also changes in the amount of meat or milk produced. The use of whole farm modelling approaches provides a powerful tool for analysing the system-wide effects of GHG mitigation measures on emissions and farm financial performance.

In addition to the systemic effects within the farm outlined above, interactions can also occur along the supply chain. For example, changing the way in which inputs such as synthetic fertilisers and feed materials are produced can change the emission intensities of the final commodities produced. These effects can be captured by using a life cycle analysis approach in the evaluation of mitigation measures.

Various whole farm models and modelling frameworks have been developed, mostly for one or two particular farming systems (see reviews of the ruminant systems by CROSSON et al., 2011, and SCHILS et al., 2007), while some are capable of simulating different farming systems (LOUHICHI et al., 2010; NEUFELDT and SCHAFER, 2008). However, LCA GHG calculations are rarely provided by these tools, therefore in this paper we outline an approach which is capable of simulating management changes on various farm systems to provide ex-ante evaluation of LCA GHG emissions and economic effects.

The farm level modelling framework presented here consists of the Global Livestock Environmental Assessment Model, a life-cycle GHG emission model (MACLEOD et al., 2013) and ScotFarm, an optimising farm level model based on a linear programming farm economic model described by SHRESTHA (2004). Within this framework, the emissions, production and farm income can be calculated with and without mitigation measures, thus enabling the cost-effectiveness of measures and the interactions between the measures to be quantified for specific-farm systems and locations.

This paper provides an explanation of the approach and a case study of sexed semen on Scottish dairy farms. Finally, the strengths and weaknesses of the approach and options for future development are discussed.

2 Methodology

2.1 GLEAM

GLEAM is an LCA model developed by the UN Food and Agriculture Organisation (MACLEOD et al., 2013). It simulates processes within livestock production systems in order to assess their environmental performance. The current version of the model (V1.0) focuses primarily on the quantification of GHG emissions and includes: (a) pre-farm emissions arising from the manufacture of inputs; (b) on-farm emissions during crop and animal production; and (c) post-farm emissions arising from the processing and transportation of products to the retail point. Emissions and food losses that arise after delivery to the retail point are not included. While gases of minor importance have been omitted, the three major GHG in agriculture are included, namely: (1) methane (mainly from enteric fermentation, manure storage and rice cultivation), (2) nitrous oxide (from soils and manure storage) and (3) carbon dioxide from (a) the combustion of fossil fuels on-farm (e.g. in tractors and generators) and off-farm (in the manufacture of inputs, including mineral fertilisers, and in post-farm processing and transport) and (b) land use change. Carbon dioxide from the short biological cycles such as respiration and aerobic decomposition are not included. GLEAM calculates:

- total production of the main livestock commodities, i.e. meat, milk and eggs
- the total greenhouse gas emissions arising from that production
- the emission intensity of each commodity.

A brief overview of the model elements is given below, and values for selected parameters given in Table 1.

The **herd module** starts with the total number of animals of a given species and system. It determines the herd structure (i.e. the number of animals in each cohort, and the rate at which animals move between cohorts) and the characteristics of the average animal in each cohort (e.g. weight and growth rate).

The **manure module** calculates the rate at which total excreted N is applied to crops, accounting for losses during storage.

The **feed module** calculates key feed parameters, i.e. the nutritional content and emissions per kg of the feed ration.

The **system module** calculates each animal cohort's energy requirement, and the total amount of meat, milk and eggs produced each year. It also calculates the total annual emissions arising from manure management, enteric fermentation and feed production.

The **allocation module** combines the emissions from the system module with the emissions calculated outside GLEAM, i.e. emissions arising from (a) direct on-farm energy use; (b) the construction of farm buildings and manufacture of equipment; and (c) post-farm transport and processing. The total emissions are then allocated to the co-products (e.g. meat and milk) and the EI of the commodities are calculated.

2.2 ScotFarm

ScotFarm, a profit optimising financial model developed at SRUC, is based on a farm level dynamic line-

Table 1. Value of selected parameters for lactating cows

Category	Parameter	Value	Notes
Ration	Ration digestibility (%)	78	Calculated, based on a ration of 62% fresh grass, 38% compound feed
Ration	Ration emissions intensity (kg CO_2e (kg DM)$^{-1}$)	1.4	Calculated using IPCC (2006) Tier 1
Intake	NE requirement (MJ cow^{-1} day^{-1})	121.8	Calculated using IPCC (2006) Tier 2
Intake	Feed intake (kg DM cow^{-1} day^{-1})	15.4	Calculated using IPCC (2006) Tier 2
Output	Volatile solid excretion (VSx) (kg cow^{-1} day^{-1})	3.64	Calculated using IPCC (2006) Tier 2
Output	N excretion (kg N cow^{-1} day^{-1})	0.39	Calculated using IPCC (2006) Tier 2
Output	Enteric methane (kg CH_4 cow^{-1} year^{-1})	109	Calculated using IPCC (2006) Tier 2
Manure	Methane conversion factor (% of VSx)	6.3	Calculated using IPCC (2006) Tier 2, based on 68% PRP, 32% slurry (no cover)
Manure	Manure methane (kg CH_4 cow^{-1} year^{-1})	13.4	Calculated using IPCC (2006) Tier 2
Other	Average annual temperature (°C)	10	Assumption
Other	Methane conversion factor (Ym) (%)	6.5	IPCC (2006, Table 10.12)
Other	B_0 (m^3 CH_4 (kg VS)$^{-1}$)	0.24	IPCC (2006, Table 10.A4)

Source: authors

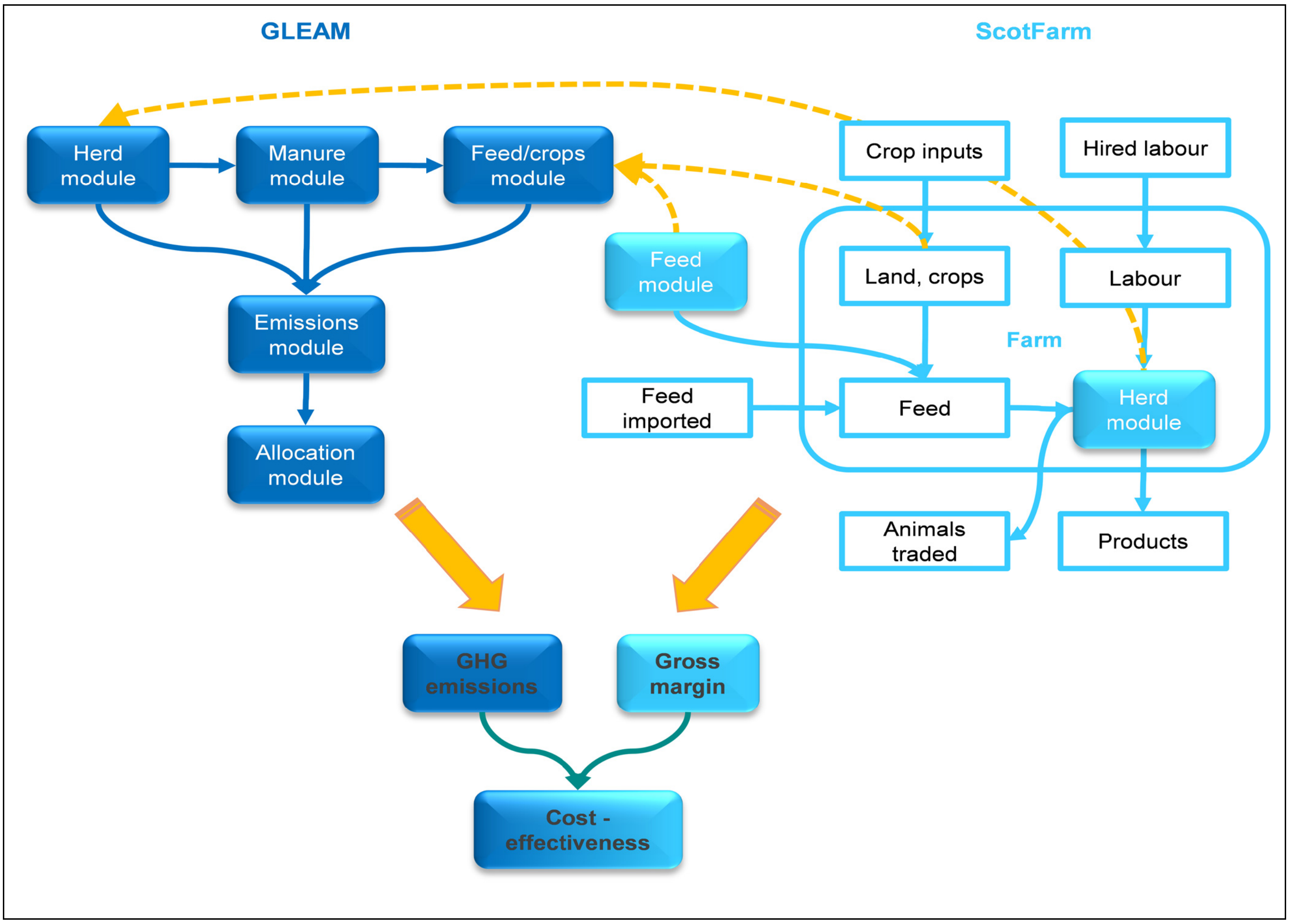
ar programming model which is described in detail in SHRESTHA (2004). Modified versions of farm level linear programming models have been used in a number of farm level analyses of Irish agriculture (SHRESTHA and HENNESSY, 2006; SHRESTHA et al., 2007, 2013; HENNESSY et al., 2008). ScotFarm assumes that all farmers are profit oriented and maximise farm net income within a set of limiting farm resources. It consists of four production systems; dairy, beef, sheep and arable. These systems are constrained by the land, labour, feed and stock replacement available to a farm. The total land available to a farm is fixed. Farms are allowed to buy in feeds, animal replacements and hire labour if required. The farm net income is comprised of the accumulated revenues collected from the final product of the farm activities (crops, animals and milk) plus farm payments minus costs incurred for inputs under those activities. The input costs are replacement costs for livestock, variable costs including labour, feed and veterinary costs and overhead costs on farms.

The model consists of all the major crops in Scotland. The initial land under these crops in each farm is based on farm level data of the 2010/11 Farm Account Survey of Scotland (see section 2.4); however, the model allows land to be reallocated between these crops as well as transferred to grass production. The stocking rate on each farm is also fixed to the farm level data assuming that all farms were operating under optimum stocking rate. The dairy system has a four year replacement structure where dairy animals are culled after every four years. Similarly beef and sheep systems follow a two year replacement structure. The animals are replaced by on-farm or off-farm replacement stocks. A feed module, based on ALDERMAN and COTTRILL (1993) is used in the model to determine feed requirements for each of the animals on a farm based on type, age and production level of the animal. Feeds available to the livestock on farm are fresh grass, grass silage, grass hay, maize silage, grains, straw, beet and concentrate feeds.

2.3 Harmonising GLEAM and ScotFarm

Model parameters, input variables and modules are harmonised in GLEAM and ScotFarm in order to

Figure 1. Conceptual framework of the two models



Source: authors

Table 2. Modelling differences between GLEAM and ScotFarm

	GLEAM	ScotFarm
Type of model	Static, deterministic calculation over 1 year	Linear programming pseudo dynamic optimisation model with yearly time-steps
System boundaries	Partial LCA: GHG emissions from cradle-to-delivery at retail point	Farm gate
Data input	Primary data such as animal numbers, herd/flock parameters, mineral fertilizer application rates, temperature, etc. derived sources such as literature, databases and surveys (see MACLEOD et al., 2013, Appendix B).	Farm level data such as land area, land use, animal numbers and labour use; and financial data such as gross margins, variable costs and overhead costs are taken from Farm Account Survey (SCOTTISH GOVERNMENT, 2011). Farm coefficients such livestock units and labour requirements are taken from The Farm Management Handbook (SAC, 2012).
Output	Total annual commodity production (meat, milk and eggs); total GHG emissions; EI of each commodity.	Farm margins, feed rationing, herd size, land use; Total annual commodity production
Dairy herd structure	Six animal categories based on reproductive use and sex, herd structure is calculated using herd parameters	Four animal categories based on age and sex; herd structure is optimised based on herd parameters and prices
Ration	Imported from ScotFarm	Endogenous – the financially optimal combination of feed materials that can meet nutritional constraints is determined. The nutritional constraints are the metabolisable energy and protein requirements based on age and production level of individual animals (ALDERMAN and COTTRILL, 1993). Each of the farm groups however has to use concentrate diet at least 50% of level available in farm level data.

Source: authors

simulate the model farms and the mitigation measures` effect in parallel in both models. The herd structure, land use and feed ration composition are optimised in ScotFarm, and then exported to GLEAM (see Figure 1).

The main conceptual differences between the models are summarised in Table 2. To simulate both the baseline farms and the mitigation options in parallel in an optimisation and a static model, constraints are built in ScotFarm so that the farm structure of the baseline farm and the farm with the mitigation measure (apart from the specific changes due to the measure) is similar (i.e. the differences in grassland and arable land areas, herd size and feed composition between the farms modelled in GLEAM and in ScotFarm are not more than 5%). First the baseline farms are simulated in ScotFarm, and the resulting optimised baseline farm characteristics (land areas, number of cows, composition of the feed rations) are fed into GLEAM along with harmonised values for input parameters common to both models (e.g. milk and crop yields). The total production (of meat and milk) and GHG emissions are calculated in GLEAM and the farm gross margin is calculated in ScotFarm (see Figure 1). The procedure is then repeated for the scenario with the mitigation measure. The changes in emissions and in the EI of products due to the mitigation measure are then calculated by comparing the results of the baseline scenario and the scenario with the measure.

2.4 Defining Farm Types

Farm level data was drawn from the 2010/11 Farm Account Survey of Scotland (SCOTTISH GOVERNMENT, 2011). The FAS consisted of farm level data from 484 farms which included physical as well as financial information of each of the sampled farms. A cluster analysis was carried out in SPSS[1] to group farms together with similar characteristics. Seven farm variables (production system, farm gross margins, land, animal number, labour, feed and milk yield) were used to group the farms. These variables were assumed to be the main differences between farms. The Squared Euclidean Distance Method was used in finding similarities between the farms. This method is commonly used in cluster analysis when there are multi-dimensional variables such as farm variables used in this study (SOLANO et al., 2001).

The cluster analysis resulted in fifteen farm types, with their main characteristics presented in (Table 3). These characteristics formed the basis of more detailed farm descriptions, which were generated

1 SPSS is a statistical software. More details are available @ http://www-01.ibm.com/software/analytics/spss/

Table 3. Typology of Scottish farms generated, based on FAS

Farm types	Grass land (ha)	Arable land (ha)	Livestock units[a] (lu)	Variable costs (€ lu^{-1})	Labour[b] (man unit)
Dairy large	227.9	0.0	284	229.4	2.3
Dairy medium	99.5	11.7	137	227.7	2.1
Beef large	234.3	15.7	222	138.1	1.7
Beef medium	139.3	8.3	166	153.4	2.0
Beef small	77.0	4.5	84	143.0	1.3
Beef/Sheep large	263.5	27.9	242	151.2	2.9
Beef/Sheep medium	93.1	4.7	106	150.5	1.6
Sheep large	126.3	0.0	171	141.4	2.1
Sheep medium	65.3	0.0	81	126.0	1.5
Crop large	178.3	229.1	7	1428.6	7.5
Crop medium	86.3	218.0	8	1151.4	2.7
Crop small	46.6	89.0	3	1177.0	1.5
Mixed large	145.1	92.1	162	116.5	2.1
Mixed small	70.0	44.0	2045	112.5	1.6
Low land Beef/Sheep	172.0	9.0	162	124.3	1.8

[a] Livestock unit: (defined in terms of feed requirement) one unit equals to the maintenance of a mature 625 kg Friesian cow and the production of a 40-45 kg calf and 4,500 l of milk per year.
[b] man unit: 2,200 working hours $year^{-1}$
Source: authors

to describe the baseline farms in terms of their cropping and livestock activities, fertiliser and feed use, crops and livestock product yields.

2.5 Case Study: Using Sexed Semen to Reduce Unwanted Male Calf Numbers on Scottish Dairy Farms

In Scottish dairy herds, a proportion of the cows are mated, usually by artificial insemination, using dairy breed semen to produce replacement stock, and the remainder are inseminated with beef semen to provide dairy x beef calves that are reared for beef production. The use of unsexed semen leads to significant number of pure dairy male calves, most of which are not required for replacement, and may be uneconomic to rear as beef animals (ROBERTS et al., 2008). This raises issues of economic and resource inefficiency and animal welfare. The use of sexed semen enables the number of cows mated with dairy semen to be reduced and the number of dairy x beef calves to be increased (see Table 4). The effect of using sexed semen on the emissions arising from dairy production and on the farm finances were investigated.

Representing common practice in Scotland, the baseline farms were assumed to use artificial insemination, using dairy semen on 70% of their cows and heifers to produce enough female dairy calves for replacement (and as a ‘by-product’ dairy male calves, which are culled as newborns), and using beef semen on the remaining females to produce crossbred calves to be sold for rearing. With using sexed dairy semen the proportion of females inseminated with dairy semen is reduced to 40%, increasing the high-value crossbred calves proportion to 60%. The mitigation measure changes the income from the calves sold and the cost of the insemination in the financial model, and has effects on the GHG emissions from the reared beef cattle and on the meat produced.

Table 4. Difference between the baseline farms and the farms with the mitigation measure implemented

Variable	Baseline: unsexed semen	With sexed semen
Proportion of female dairy replacement calves	0.35	0.35
Proportion of male dairy calves	0.35	0.05
Proportion of crossbred calves	0.30	0.60
Increase in the variable cost due to using sexed semen (€ lu^{-1})	-	11.7

Source: authors

The sexed semen mitigation method is only applicable on farms with dairy cattle: i.e. dairy and mixed farms, but it less relevant to mixed farms due to the much lower number of dairy cattle there, therefore only the medium and large dairy farms were modelled in this case study. The main farm characteristics are presented in Table 5.

Two important parameters in the financial and EI reduction performance of the mitigation measure are the additional cost of using the sexed dairy semen and the assumption on the EI of the suckler beef the additional crossbred calves are replacing. Sensitivity analysis was undertaken to explore the influence of these assumptions on cost-effectiveness.

Table 5. Main characteristics of the modelled baseline

Variable	Medium dairy farm	Large dairy farm
System: Year round calving, pasture based summer grazing for eight months, winter housing with grass silage feed, feed supplemented with concentrates and minerals year round.		
Number of cows (head)	149	300
Arable land area (ha)	11	0
Permanent grassland area (ha)	100	228
Milk sold (kg head^{-1} year^{-1})	6,000	7,000
Milk price (€ l^{-1})	0.27	0.28
Crossbred calves' price (€ head^{-1})	100	86
Cow weight (kg head^{-1})	540	
Fertility rate of cows	0.87	
Fertility rate of heifers	0.95	
Calving period	all year	
Calving interval (month)	12	
Age at first calving (month)	28	
Replacement rate	0.25	
Milk wastage ratio ((milk secreted – milk sold) / milk secreted)	0.09	
Suckler beef EI (kg CO_2e (carcass weight)$^{-1}$)	30	

Source: authors

3 Results

Production, GHG emission and gross margin data of the baseline farms and the effect of using sexed semen are shown in Table 6. Producing more crossbred calves by using sexed semen increased the meat production of the systems by 47% for both medium and large dairy farms, while having no effect on milk production. This leads to an increase in the EI of the total protein produced, as a greater proportion of the protein is meat, which has a higher EI than milk. However, simply comparing the farms with and without sexed semen in term of the EI per unit of protein is misleading, as they are producing milk and meat in different proportions. In order to compare like with like, systems expansion can be used to isolate the emissions attributable to milk only. This is done by calculating the emissions that are avoided by producing beef, and subtracting these from the total emissions, to leave the emissions attributable to milk. In this

Table 6. Production, GHG emission and gross margin data of the dairy farms with and without sexed semen

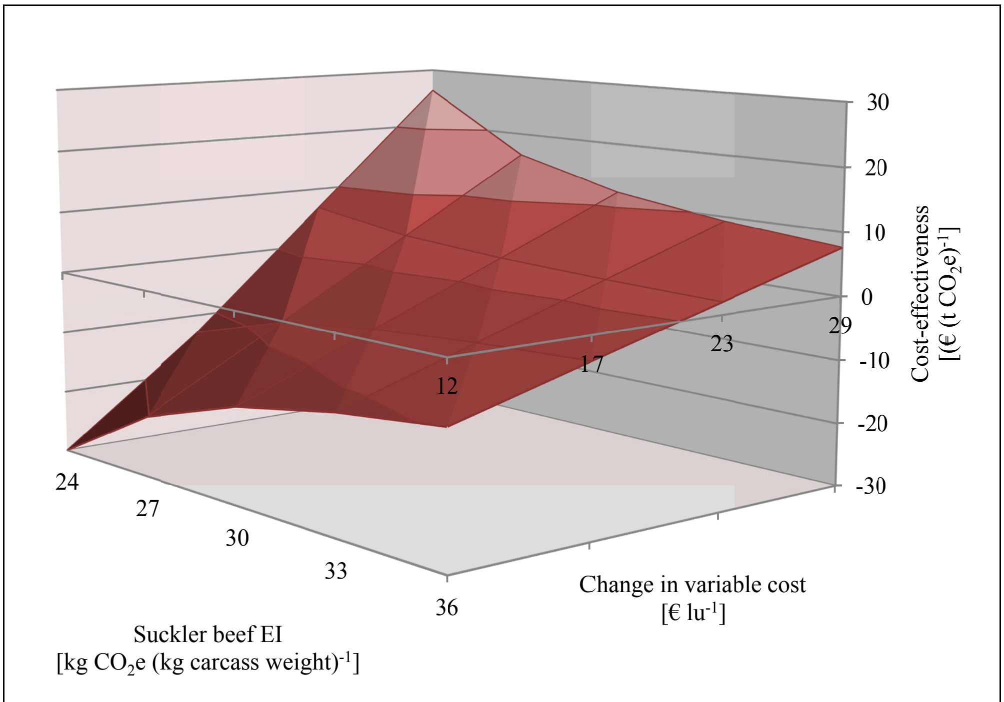
		Medium dairy farm		Large dairy farm	
		Baseline	With SS[a]	Baseline	With SS
Production (kg protein year^{-1})	Meat	3,315	4,878	6,675	9,822
	Milk	29,591	29,591	68,815	68,815
GHG emissions for milk and meat (kg CO_2e year^{-1})		2,144,750	2,366,120	4,559,644	5,005,356
EI of milk and meat protein (kg CO_2e (kg protein)$^{-1}$)		65.2	68.6	60.4	63.7
GHG emissions for milk only (kg CO_2e year^{-1})		1,408,063	1,282,078	3,026,939	2,677,212
Milk EI (kg CO_2e (kg milk)$^{-1}$)		1.58	1.43	1.46	1.29
Gross margin (€ year^{-1})		165,284	167,128	261,569	264,120
Effect of mitigation measure		**Medium dairy farm**		**Large dairy farm**	
Change in milk GHG with SS (kg CO_2e year^{-1})		-125,984		-349,727	
Change in gross margin with SS (€ year^{-1})		1,844		2,552	
Cost-effectiveness of SS (€ (t CO_2e)$^{-1}$)		-14.64		-7.30	

[a]SS: sexed semen
Source: authors

example it is assumed that if the beef was not produced by the surplus dairy calves, it would have to be produced by specialised (i.e. cow-calf) beef production. This type of beef production typically has significantly higher EI than that of dairy beef (see OPIO et al., 2013). It was assumed that the avoided specialised beef had an EI of 30 kg CO_2e (kg carcass weight)$^{-1}$. Under these assumptions, the EI of the milk is reduced by the mitigation measure by 9% and 12% on medium and large dairy farms, respectively. The financial modelling shows that the additional income from the increased number of marketable calves is more than 2.5 times more than the cost of sexed semen administration on both of the dairy farms. Therefore the cost-effectiveness of the measure on medium and large dairy farms is -15 and -7 € (t CO_2e)$^{-1}$, respectively.

The sensitivity analysis shows that varying the EI of the suckler beef by +20% and -20% changes the abatement potential by +55% and -55%, respectively, while changing the variable cost (due to sexed semen administration) by +50% reduces the net savings by 60% and increasing it by 100% or more makes a loss to the farmer. Overall, the cost-effectiveness of the measure varies between -33 and +27 € (t CO_2e)$^{-1}$ (Figure 2).

Figure 2. Sensitivity of the cost-effectiveness to the price of the sexed semen and the EI of the suckler beef



Source: authors

4 Discussion

Developing more efficient agri-environmental policies requires the cost-effectiveness of GHG mitigation measures on different farm types to be quantified. The modelling framework proposed in this study provides this capacity, by using a financial optimisation model to simulate the gross margin changes and an LCA GHG model to estimate the emission changes arising from the mitigation measures. Adopting an LCA-approach in these calculations helps to ensure that mitigation measures do not simply displace emissions to other parts of the supply chain (although the danger of displacing production and emissions to other regions of the world still remains).

The current case study presents Scottish dairy farms as an example; however, both GLEAM and ScotFarm have the flexibility to model a wide variety of farm types and locations, provided input data of the requisite type and quality is available. Further benefits of the framework are the consistency in assumptions across mitigation measures and farm types and the inclusion of LCA and economic aspects to the whole farm modelling.

The modelling framework also has its limitations. The IPCC (2006) Tier 2 approach (PAUSTIAN et al., 2006) to livestock and manure emissions used in GLEAM provides considerable scope for varying livestock parameters and, in doing so, the modelling of mitigation measures. However, the Tier 1 approach to crop/soil emissions provides less scope (for example changes in the timing of fertiliser application or differences between soil types cannot be captured directly) and will be refined in the future versions of the model. The same applies to ScotFarm, where the cost breakdown distinguishes between labour, variable costs and overhead costs, therefore the mitigation measures have to be described according to their effects on these variables rather than on more detailed farm activities. Nevertheless, these features also provide flexibility, as data collection at this level is quicker and often easier than acquiring farm type specific detailed activity and financial data. Therefore, the results should be interpreted as for the 'typical' farm in the modelled region rather than specific to one individual farm. It is also important to mention that the current framework does not capture the co-effects of GHG mitigation on other pollutants. These effects – especially on other types of reactive N (e.g. ammonia and nitrate) – can be significant for some mitigation measures, gaining even higher importance in regions with high nitrogen pollution. Nevertheless, these linked models provide a flexible and consistent way of calculating mitigation cost-effectiveness in a range of farm systems, helping to design better targeted regional and national policies for agriculture.

The results of the case study example show that using sexed semen on dairy farms might be a cost-effective way (i.e. cheaper than the shadow price of carbon), in some circumstances even win-win opportunity (i.e. providing financial savings to the farmers) to reduce emissions from cattle production. An important aspect of this GHG mitigation is that the GHG savings do not occur directly on the farm. High-yielding, specialised dairy and beef systems are interlinked via the surplus calves in the dairy herds which can potentially be reared for meat and also via beef cross females from dairy herd becoming suckler cows. In the case of using sexed semen, the EI of the whole cattle system improves by decreasing the number of unwanted dairy male calves and increasing the amount of lower EI 'dairy beef' produced. The sensitivity analysis show that the measure stops generating financial savings on the farm after the additional cost of administering sexed semen exceeds approximately 21 € lu^{-1}. Similarly, the GHG savings are highly sensitive to the assumption on the emission intensity of the suckler beef production in the cattle system. The overall cost of sexed semen administration for the farmer depends not only on the cost of the semen but also on a number of factors related to fertility and herd management, like conception rate differences between cows and heifers, the availability of skilled personnel for the fertilisation, and the availability of sexed semen from high genetic merit sires. Providing more information and support in these areas to farmers would therefore increase the likelihood of the farmers achieving financial savings by using sexed semen in dairy herds. All in all, the feasibility of integrating sexed semen use into the Scottish Government's GHG mitigation policy should be investigated.

References

ALDERMAN, G. and B.R. COTTRILL (1993): Energy and protein requirements of ruminants. An advisory manual prepared by the AFRC Technical Committee on responses to nutrients. CAB International, Wallingford, UK.

ALEXANDRATOS, N. and J. BRUINSMA (2012): World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. FAO, Rome.

BELLARBY, J., R. TIRADO, A. LEIP, F. WEISS, J.P. LESSCHEN and P. SMITH (2013): Livestock greenhouse gas emissions and mitigation potential in Europe. In: Global Change Biology 19 (1): 3-18.

COTTLE, D.J., J.V. NOLAN and S.G. WIEDEMANN (2011): Ruminant enteric methane mitigation: a review. In: Animal Production Science 51 (6): 491-514.

CROSSON, P., L. SHALLOO, D. O'BRIEN, G.J. LANIGAN, P.A. FOLEY, T.M. BOLAND and D.A. KENNY (2011): A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. In: Animal Feed Science and Technology 166-167: 29-45.

FORESIGHT (2011): The Future of Food and Farming: Challenges and choices for global sustainability. The Government Office for Science, London.

GERBER, P., T. VELLINGA, K. DIETZE, A. FALCUCCI, G. GIANNI, J. MOUNSEY, L. MAIORANO, C. OPIO, D. SIRONI, O. THIEME and V. WEILER (2010): Greenhouse Gas Emissions from the Dairy Sector - A Life Cycle Assessment. FAO, Rome.

HENNESSY, T., S. SHRESTHA and M. FARRELL (2008): Quantifying the viability of farming in Ireland: can decoupling address the regional imbalances? In: Irish Geography 41 (1): 29-47.

HRISTOV, A., J. OH, C. LEE, R. MEINEN, F. MONTES, T. OTT, J. FIRKINS, A. ROTZ, C. DELL, A. ADESOGAN, W.Z. YANG, J. TRICARICO, E. KEBREAB, G.C. WAGHORN, J. DIJKSTRA and S. OOSTING (2013): Mitigation of greenhouse gas emissions in livestock production – A review of technical options for non-CO_2 emissions. In: Gerber, P., B. Henderson and H. Makkar (eds.): FAO Animal Production and Health Paper 177. FAO, Rome.

IPCC (Intergovernmental Panel on Climate Change) (2006): 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. In: Eggleston, H.S., L. Buendia, K. Miwa, T. Ngara and K. Tanabe (eds.). Institute for Global Environmental Strategies (IGES), Japan.

– (2013): Summary for Policymakers. In: T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.): Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate

Change, WGI AR5 PM. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

LOUHICHI, K., A. KANELLOPOULOS, S. JANSSEN, G. FLICHMAN, M. BLANCO, H. HENGSDIJK, T. HECKELEI, P. BERENTSEN, A.O. LANSINK and M.V. ITTERSUM (2010): FSSIM, a bio-economic farm model for simulating the response of EU farming systems to agricultural and environmental policies. In: Agricultural Systems 103 (8): 585-597.

MACLEOD, M., P. GERBER, A. MOTTET, G. TEMPIO, A. FALCUCCI, C. OPIO, T. VELLINGA, B. HENDERSON and H. STEINFELD (2013): Greenhouse gas emissions from pig and chicken supply chains – A global life cycleassessment. FAO, Rome.

NEUFELDT, H. and M. SCHAFER (2008): Mitigation strategies for greenhouse gas emissions from agriculture using a regional economic-ecosystem model. In: Agriculture Ecosystems & Environment 123 (4): 305-316.

OPIO, C., P. GERBER, A. MOTTET, A. FALCUCCI, G. TEMPIO, M. MACLEOD, T. VELLINGA, B. HENDERSON and H. STEINFELD (2013): Greenhouse gas emissions from ruminant supply chains – A global life cycleassessment. FAO, Rome.

ROBERTS, D.J., J. BELL, K. BEVAN and T. MCEVOY (2008): Beyond calf exports: the efficacy, economics and practicalities of sexed semen as a welfare-friendly herd replacement tool in the dairy industry. Report produced for Compassion in World Farming & The Royal Society for the Prevention of Cruelty to Animals. Scottish Agricultural College, Edinburgh.

SAC (Scottish Agricultural College) (2012): The farm management handbook 2012/13. SAC Consulting, Edinburgh.

SCHILS, R.L.M., J.E. OLESEN, A. DEL PRADO and J.F. SOUSSANA (2007): A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. In: Livestock Science 112 (3): 240-251.

SCOTTISH GOVERNMENT (2011): Economic report on Scottish Agriculture. Rural and Environment Science and Analytical Services (RESAS), Scottish Government. In: http://www.scotland.gov.uk/Publications/2011/06/15143401/0.

SHRESTHA, S. (2004): Adaptation strategies for dairy farms in central and north-west England under climate change. PhD thesis. University of Nottingham.

SHRESTHA, S. and T. HENNESSY (2006): Changes in land use on farms in the Border and the Mid-East regions of Ireland after decoupling of farm payments. Agricultural Research Forum, 15-16 March, Tullamore, Ireland.

SHRESTHA, S., T. HENNESSY and S. HYNES (2007): The effect of decoupling on farming in Ireland: a regional analysis. In: Irish Journal of Agriculture and Food Research 46 (1): 1-13.

SHRESTHA, S., P. CIAIAN, M. HIMICS and B. VAN DOORSLAER (2013): Impacts of climate change on EU agriculture. In: Review of Agricultural and Applied Economics 16 (2): 24-39.

SOLANO, C., H. LEON, E. PEREZ and M. HERRERO (2001): Characterising objectives profiles of Costa Rican dairy farmers. In: Agricultural Systems 67 (3): 153-179.

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